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# Production of Supersymmetric Higgs Bosons at LEP $\otimes$ LHC

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**Abstract**

Within the Minimal Supersymmetric Standard Model (MSSM), we study the production of the neutral scalar and pseudoscalar as well as the charged Higgs bosons together with fermions or sfermions in deep inelastic $ep$ scattering at $\sqrt{s} = 1.6$ TeV. We focus on the parameter space where a Higgs particle is likely to be invisible at LEP2 and LHC. Although we choose gaugino/higgsino mixing scenarios that maximize the corresponding production rates we find only for the production of the scalar Higgs bosons in the non-supersymmetric channels non-negligible cross sections of the order of $10^2$ fb.

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# 1 Introduction

After the observation of the top quark [1] the Higgs boson remains the last experimentally undetected component of the standard model (SM). The discovery of a Higgs particle could not only lead to a deeper understanding of the origin of mass and the nature of electroweak symmetry breaking in the framework of the SM, but may also provide an essential hint for models with an enlarged Higgs sector. Supersymmetric theories offer the most attractive possibility for such extended models. While in the SM there exists only one scalar Higgs boson, the Minimal Supersymmetric Standard Model (MSSM) contains two Higgs doublets with vacuum expectation values $v_1$ and $v_2$ ($\tan\beta = v_2/v_1$) leading to five physical Higgs bosons, namely two neutral scalars $h$ and $H$ ($m_H > m_h$), one neutral pseudoscalar $A$ and a pair of degenerate charged Higgs bosons $H^{\pm}$. The masses of the scalar Higgs particles and their mixing angle $\alpha$ can be parametrized in terms of two parameters which are normally chosen to be $m_A$ and $\tan\beta$.

With the next generation of high energy colliders the search for the Higgs boson in the SM as well as in the MSSM enters a new phase. Unfortunately, for both models the proposed new colliders LEP2 and LHC may probably leave a significant region of the possible Higgs masses uncovered [2]. Therefore one has to think of further colliders in order to be sensitive to the full parameter space of the Higgs sector. The next possible step could be the construction of a new $ep$ machine by combinating LEP2 and LHC. In the SM, the cross section for Higgs production by electron proton scattering is known to be of the order of $10^2$ fb [3, 4], therefore being on the edge of the discovery limit. In this letter we want to study the prospects for discovering a MSSM Higgs boson at LEP $\otimes$ LHC with a center of mass energy $\sqrt{s} = 1.6$ TeV.

The present experimental mass limits for a Higgs boson are based on the negative Higgs search at LEP1. For the SM Higgs boson the mass is found to be larger than 63.5 GeV [5] while the lower mass bounds for the scalar and pseudoscalar Higgs particles in the MSSM are 44 GeV ($\tan\beta > 1$) and 21 GeV, respectively [6]. The resulting excluded parameter space in the $(m_A, \tan\beta)$ plane of the MSSM is given in [2] together with the accessible domains by LEP2 and LHC. Here, identification of a Higgs boson is expected to be possible by the decay channels $h, H \longrightarrow ZZ \longrightarrow 4$ leptons for $m_{h,H} > 2m_Z$, or $h, H \longrightarrow \gamma\gamma$. While the 4-lepton channel provides a clear signal easy to classify, the 2-photon final state also leads to a favorable signature but is mostly heavily suppressed. We focus in our analysis of Higgs production at $ep$ colliders on the region 100 GeV $< m_A <$ 200 GeV, $5 < \tan\beta < 10$, where the Higgs boson dominantly decays into $b\bar{b}$ pairs that are difficult to discriminate from QCD background. For larger values of $\tan\beta$ the Higgs mass range uncovered by LEP2 and LHC significantly shrinks.

Production of a SM Higgs in $ep$ scattering in the corresponding mass region 80 GeV $\lesssim m_h \lesssim$180 GeV by $W$ fusion including QCD and QED corrections was recently studied by Blümlein et al. [4]. We extend this analysis to scalar, pseudoscalar and charged Higgs bosons of the MSSM. Since in [4] the first order QCD and leading QED corrections were found to be as small as of the order of a few percent of the total cross section, we restrict ourselves to the Born level, but consider all Higgs-fermions as well as Higgs-sfermions production channels. As it turns out, in the parameter space inaccessible to LEP2/LHC, only the cross sections for the production of the neutral scalars reach sizeable values. But

they maximally reach the SM values so that the analysis of Ref. [4] is applicable, or they are too small for a reliable identification of the Higgs. In every case, an *ep* collider LEP $\otimes$ LHC does not seem well suited for the Higgs search in the MSSM in the parameter space not covered by LEP2 and LHC. So an $e^+e^-$ collider with a center-of-mass energy of 500 GeV appears to be absolutly necessary in order to explore the full MSSM parameter space in the Higgs sector.

This paper is organized as follows: In Sec. 2 we present the different production channels and choose typical scenarios. The discussion of the numerical results follows in Sec. 3

# 2 Production channels and scenarios

Higgs boson production by deep inelastic *ep*-scattering takes place in processes with either a lepton and a quark or a scalar lepton and a scalar quark in the final state. The corresponding Feynman graphs are shown in Fig. 1.

The neutral scalar Higgs bosons are produced together with both fermions or sfermions where all Feynman graphs of Fig. 1 contribute. Here, associated Higgs-neutrino production proceeds via $W$-fusion, while $Z$-fusion leads to associated Higgs-electron production (Fig. 1 (a)). The cross sections are related to those in the standard model [3, 4] by

$$\sigma(ep \to hlqX) = \sin^2(\alpha-\beta)\sigma(ep \to H_{SM}lqX) \tag{1}$$

$$\sigma(ep \to HlqX) = \cos^2(\alpha-\beta)\sigma(ep \to H_{SM}lqX) \tag{2}$$

where $\alpha$ is the mixing angle between the two Higgs states.

Production of a neutral Higgs boson with two sfermions is described by the Feynman graphs in Fig. 1 (b) - (d).

The neutral pseudoscalar Higgs and the charged Higgs bosons can be produced only in the supersymmetric channels $ep \to A\tilde{l}\tilde{q}X$, $H^\pm\tilde{e}\tilde{q}X$, $H^-\tilde{\nu}\tilde{q}X$. However, not all supersymmetric graphs in Fig. 1 (b) - (d) contribute to all of these processes. So the production of the pseudoscalar Higgs is only mediated via neutralino/chargino fusion (c) when the Yukawa couplings of the first two generations are neglected.

The scenarios for the numerical calculation comply with two requirements. First, Higgs bosons are not detectable neither at LEP2 nor at LHC. Therefore we vary the mass of the pseudoscalar Higgs from 100 to 200 GeV at $\tan\beta = 5$. These parameters cover all for the Higgs production relevant values of the Higgs masses (Fig. 2) and of the reduction factor $\sin^2(\alpha-\beta)$ (Fig. 3). Radiative corrections to the Higgs masses and mixings due to top/stops loops are included with $A_t = 0$ GeV and the stop masses $m_{\tilde{t}_1} = 150$ GeV, $m_{\tilde{t}_2} = 500$ GeV.

Second, the parameters of the gaugino/higgsino sector lead to maximal production rates in the channels with sfermions. Generally this happens if the lightest neutralino assumed to be the lightest supersymmetric particle (LSP) is a mixture of higgsino and zino eigenstate. So we choose for the $SU(2)$ gaugino mass $M = 220$ GeV and for the parameter in the superpotential $\mu = 160$ GeV leading to a LSP with a mass of 84 GeV. As usual we assume for the $U(1)$ gaugino mass in the neutralino mixing matrix the GUT relation $M' = \frac{5}{3}\tan^2\theta_W M \approx 0.5M$.

All calculations are performed for a center of mass energy $\sqrt{s} = 1.6$ TeV and slepton and squark (apart from the stop) masses $m_{\tilde{l}} = 100$ GeV, $m_{\tilde{q}} = 200$ GeV well beyond the current experimental limits.

For the production of massless fermions ($ep \to hlqX, HlqX$) the squared momentum transfer at the quark vertex $\tilde{Q}^2$ entering the quark distribution functions $q(\tilde{Q}^2, x)$ is given by $Q^2_{hadr.} = -(p_{q_{out}} - p_{q_{in}})^2$. In this case we impose a cut for $\tilde{Q}^2$ with $Q^2_{cut} = 0.25(\mathrm{GeV})^2$, which is the lower bound for $\tilde{Q}^2$ leaving the quark distribution functions [7] still valid. For the production of massive sfermions we do not need such a cut. But on the other side the calculation of the squared momentum transfer $\tilde{Q}^2$ in the quark distribution functions becomes more complicated. For the Feynman graphs (b) and (d) this momentum transfer is given by $\tilde{Q}^2 = Q^2_{hadr.} = -(p_{\tilde{q}} - p_q)^2$, whereas in case of graph (c) $\tilde{Q}^2$ is given by $Q^2_{lept.} = -(p_{\tilde{l}} - p_e)^2$. All calculations are based on the formula [8]

$$\begin{aligned} \sigma &= \int |\mathcal{M}_b + \mathcal{M}_d|^2 q(Q^2_{hadr.}, x) + 2\mathrm{Re}(\mathcal{M}_b\mathcal{M}_c^* + \mathcal{M}_d\mathcal{M}_c^*)\sqrt{q(Q^2_{hadr.}, x)}\sqrt{q(Q^2_{lept.}, x)} \\ &\quad + |\mathcal{M}_c|^2 q(Q^2_{lept.}, x)\, \mathrm{d}Lips\, \mathrm{d}x, \end{aligned} \tag{3}$$

For the remaining parameters of the SM we use $\sin^2\theta_W = 0.228$ and $m_Z = 91.2$ GeV.

# 3 Numerical results

The results for the production of the neutral scalar Higgs bosons together with neutrinos or electrons are shown in Fig. 4. Since both the masses of the Higgs bosons and the parameter $\sin^2(\alpha - \beta)$ influence significantly the cross sections, the results have to be interpreted with the help of Figs. 2 and 3. In the case of the production of the lighter Higgs boson $h$ the cross section increases between $m_A = 100$ GeV and 200 GeV due to the increasing values of $\sin^2(\alpha - \beta)$ while the mass of the lighter Higgs boson is nearly constant in this range ($m_h = 85$ GeV for $m_A = 100$ GeV and $m_h = 98$ GeV for $m_A = 200$ GeV). For large values of the pseudoscalar Higgs mass it approaches the respective results of the SM. The strong decrease of the cross section for $H$ as a function of $m_A$ is a result of both the increase of its mass and the decrease of $\cos^2(\alpha - \beta)$ approaching 0 for large values of $m_A$.

Generally, the cross sections for Higgs-neutrino production dominate over those for Higgs-electron production, but both are at the order of $10^2$ fb and close to their standard model values [4].

In Table 1 we give some typical results for Higgs-sfermion production. Even in this most optimistic supersymmetric scenario the cross sections are all smaller than $2 \cdot 10^{-4}$ pb. The main contributions are given by the Feynman graph Fig. 1 (d) with neutralino/chargino fusion whereas the graphs Fig. 1 (b) and (c) are of minor importance. Since our scenario with the LSP being a higgsino/gaugino mixture maximizes the total cross section and especially also the contribution from graph (d), it suppresses the contributions from graphs (b) and (c). The largest cross sections of order $10^{-1}$ fb are obtained for the production of a sneutrino together with any kind of Higgs or for the associated production of charged Higgs bosons arising by strong chargino couplings. Especially the $\tilde{\nu}H^-$-production is that one with the biggest cross section due to the strong chargino

couplings at the leptonic vertex. On the other side we get the smallest cross sections for the associated production of selectrons and heavy neutral Higgs bosons (scalar as well as pseudoscalar). Even for our rather small values of $m_{\tilde{l}}$ and $m_{\tilde{q}}$, the large total sum of the masses of the particles produced in the supersymmetric channels ($\geq 400$ GeV) generally leads to these small cross sections.

# 4 Conclusion

Cross sections for the production of the neutral scalar and pseudoscalar as well as the charged Higgs bosons by deep inelastic $ep$ scattering with $\sqrt{s} = 1.6$ TeV were computed within the MSSM. We focussed on that part of the MSSM parameter space inaccessible both to LEP2 and to LHC. While the pseudoscalar and charged Higgs bosons can be produced only together with sfermions with negligibly small cross sections, the associated scalar Higgs-neutrino production reaches sizeable cross sections of the order of $10^2$ fb comparable to the standard model and leads to the typical signature $b\bar{b}\ \not{E}$. The prospects for detecting a Higgs boson at LEP $\otimes$ LHC, however, strongly depend on the hadronic background. This background arises mainly by the basic subprocess $eg \to eb\bar{b}$ where the collinear electron escapes detection. Cuts on transverse missing Energy $\not{E}_T$ and detailed Monte Carlo studies are necessary to answer the question whether this background is reducible. Another interesting signature of Higgs production could arise by the Higgs decay into a $\tau$ pair, with a rather small background from the subprocess $eq \to \nu ZX$, $Z \to \tau\bar{\tau}$ [9]. For this signature, however, a larger luminosity than $10^3\text{pb}^{-1}$/year as expected for LEP $\otimes$ LHC may be necessary.

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# Figure Captions

1. Feynman graphs for the processes $ep \to hlqX$, $HlqX$ (a) and $ep \to h\tilde{l}\tilde{q}X$, $H\tilde{l}\tilde{q}X$, $A\tilde{l}\tilde{q}X$, $H^{\pm}\tilde{e}\tilde{q}X$, $H^{-}\tilde{\nu}\tilde{q}X$ (b), (c), (d).

2. Masses of the two neutral scalar Higgs bosons $h$, $H$ as a function of $m_A$ for $\tan\beta = 5$, $A_t = 0$ GeV, $m_{\tilde{t}_1} = 150$ GeV, $m_{\tilde{t}_2} = 500$ GeV.

3. $\sin^2(\alpha - \beta)$ as a function of $m_A$ for $\tan\beta = 5$, $A_t = 0$ GeV, $m_{\tilde{t}_1} = 150$ GeV, $m_{\tilde{t}_2} = 500$ GeV.

4. Cross sections for the associated Higgs-lepton production with $\tan\beta = 5$, $A_t = 0$ GeV, $m_{\tilde{t}_1} = 150$ GeV, $m_{\tilde{t}_2} = 500$ GeV.

# Table Caption

1. Cross sections for $m_A = 100$ GeV and $m_A = 200$ GeV for the associated Higgs-slepton production with $M = 220$ GeV, $\mu = 160$ GeV, $\tan\beta = 5$, $A_t = 0$ GeV. The results are obtained with slepton and squark (apart from the stop) masses $m_{\tilde{l}} = 100$ GeV, $m_{\tilde{q}} = 200$ GeV and stop masses $m_{\tilde{t}_1} = 150$ GeV, $m_{\tilde{t}_2} = 500$ GeV.

| | $m_A = 100$ GeV | $m_A = 200$ GeV |
|---|---|---|
| $ep \to h\tilde{\nu}\tilde{q}X$ | 0.03 fb | 0.06 fb |
| $ep \to H\tilde{\nu}\tilde{q}X$ | 0.1 fb | 0.03 fb |
| $ep \to h\tilde{e}\tilde{q}X$ | 0.01 fb | 0.01 fb |
| $ep \to H\tilde{e}\tilde{q}X$ | 0.007 fb | 0.002 fb |
| $ep \to H^-\tilde{\nu}\tilde{q}X$ | 0.18 fb | 0.08 fb |
| $ep \to H^-\tilde{e}\tilde{q}X$ | 0.08 fb | 0.03 fb |
| $ep \to H^+\tilde{e}\tilde{q}X$ | 0.035 fb | 0.01 fb |
| $ep \to A\tilde{\nu}\tilde{q}X$ | 0.055 fb | 0.02 fb |
| $ep \to A\tilde{e}\tilde{q}X$ | 0.006 fb | 0.002 fb |

Table 1